Basic Energy Sciences

Interfacial Materials
Materials Science Division

Studies of Polarization Domains in Nanostructured Ferroelectric Thin Films

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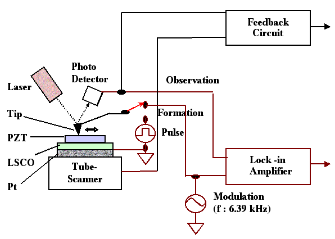
SCIENTIFIC ACHIEVEMENT

We investigated ferroelectric domain dynamics at the nanoscale, through evaluation of domain structure, stability,and relaxation as a function of ferroelectric layer microstructure and controlled capacitor size and geometry. This was achieved by using a piezoresponse imaging method based on the detection of the local electromechanical vibration of polarized domains in a ferroelectric sample, caused by an external AC voltage applied between an atomic force microscope (AFM) tip (movable top electrode) and an electrode layer underneath the ferroelectric layer [Fig. 1 (A)]. The AC electric field with a frequency ω causes a localized sample vibration whit the same frequency due to the piezoelectric effect [Fig. 1(B)]. Simultaneously with the AC excitation, a conventional topographic image can be obtained. The ferroelectric domain structure is visualized by monitoring the first harmonic signal (piezoresponse signal). The phase of the piezoresponse signal depends on the sign of the piezoelectric coefficient, such that regions with opposite polarization orientation, vibrating in counter phase with respect to each other, under the applied AC field, appear as regions of different contrast in the piezoresponse image [Fig. 1 (c)]

SIGNIFICANCE

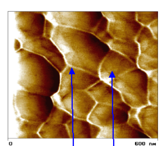
The understanding of the nanoscale ferroelectric thin film domain dynamics shown above will have a critical impact in the design f the next generation of high density (Mbit to Gbit) non-volatile ferroelectric random access memories (NVFRAMs), which can replace current DRAM and flash memories, creating a new multibillion dollar market.

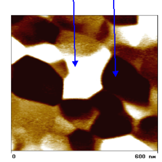
TOF-ISARS SYSTEM



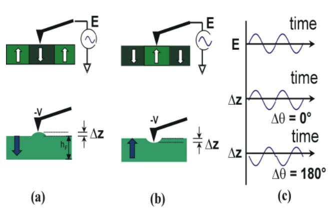
Schematic of AFM piezoresponse imaging system for nanoscale studies of ferroelectric domain evolution in ferroelectric films.

Topography Image



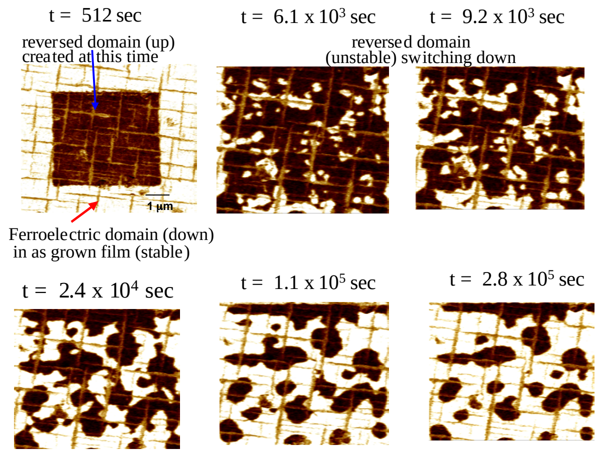


Piezoresponse Domain Image



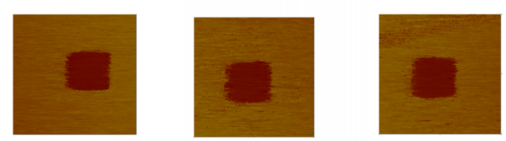
Schematic of polarization domains created in the ferroelectric film by application of electric fields between the top electrode (AFM tip) and the bottom electrode layer of a capacitor

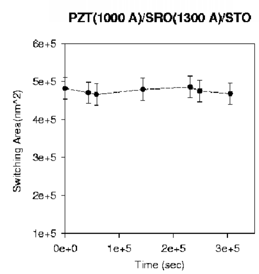
Study of polarization retention in a polycrystalline $Pb(Zr_{0.2},Ti_{0.8})O_3$ film



Switched domain stability (polarization retention) as a function of time in a $Pb(Zr_{0.2},Ti_{0.8})O_3$film. Switching starts at 90˚ domain regions indicated by straight lines in the piezoresponse images

Study of polarization retention in single crystal Pb $(Zr_{0.3}Ti_{0.7})$ O_3 Film (100 nm) on single crystal $SrRuO_3/SrTiO_3$ substrate

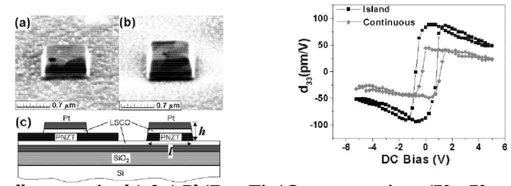




Created poled region by applying a DC voltage pulse (– 8 V) during scannig on the Surface of an expitaxial PZT film grown on a single crystal $SrRuO_3/SrTiO_3$ substrate

700 nm x 700 nm Domain in 100 nm Epitaxial PZT film remains stable over 1 week, indicating a much higher stability of polarization domains as compared with the poly-crystalline PZT fims

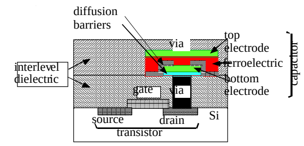
Study of polarization switching in polycrystalline $Pb(Zr_{0.2},Ti_{0.8})O_3$ film-based capacitors with nanoscale dimension fabricated with a focused ion beam



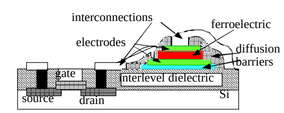
Laterally constrained (a&c) $Pb(Zr_{0.2},Ti_{0.8})O_3$nanocapacitors (70 x 70 nm) exhibit lower polarization (e) than similar unconstrained (b&d) nanocapacitors

Application of the Science of Ferroelectric Domains to Non-volatile Ferroelectric Memories

capacitor structures { $Pt/SrBi_2Ta_2O_9$ /Pt or Pt/cond. oxide/$Pb(Zr_x Ti_{1-x})O_3$ /cond. oxide/Pt



VERTICAL HIGH DENSITY NVFRAM ARCHITECTURE



LATERAL LOW DENSITY NVFRAM ARCHITECTURE

CONCLUSIONS

Studies of ferroelectric domain stability in polycrystalline and single crystalline PZT thin films, using the nanoscale resolution AFM piezoresponse imaging technique at ANL, demonstrated that single crystal PZT films exhibit much longer polarization retention than polycrystalline PZT films, which make the single crystal UNCD a good candidate material of the fabrication of NVFRAM

FUTURE WORK

- **Study of polarization domains and ferroelectric properties of PZT-based nanocapacitors, at the nanoscale, using the AFM piezoresponce imaging technique**
- **Investigation of new layered ferroelectric materials that may exhibit high polarization in nanocapacitors**